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RFCAG2013: Russian-Finnish comparison of absolute gravimeters in 2013

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Abstract: In June–July 2013, we performed a comparison of five absolute gravimeters of different types. The gravimeters were the FG5X-221 of the FGI, the FG5-110 and GBL-M 002 of the TsNIIGaiK, the GABL-PM of the IAE SB RAS, and the GABL-M of the NIIMorGeofizika (Murmansk, Russia). The three last-mentioned are field-type portable gravimeters made by the Institute of Automation and Electrometry in Novosibirsk, and this is the first international comparison for them. This Russian-Finnish Comparison of Absolute Gravimeters RFCAG2013 was conducted at four sites with different characteristics: at the field sites Pulkovo and Svetloe near St. Petersburg, and at the laboratory sites TsNIIGaIK in Moscow and Zvenigorod near Moscow. At the TsNIIGAiK site and at Zvenigorod two piers were used, such that altogether six stations were occupied. The FG5X-221 provides the link to the CCM.G-K2 Key Comparison in Luxembourg in November 2013. Recently, the Consultative Committee for Mass and Related Quantities and the International Association of Geodesy drafted a strategy on how to best transmit the results of Key Comparisons of absolute gravimeters to benefit the geodetic and geophysical gravimetric community. Our treatment of the RFCAG2013 presents one of the first practical applications of the ideas of the strategy document, and we discuss the resulting uncertainty structure. Regarding the comparison results, we find the gravimeters show consistent offsets at the quite different sites. All except one gravimeter are in equivalence.

Keywords: absolute gravimeter; field absolute gravimeter; gravimeter comparison; key comparison

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1 Introduction

In addition to the comprehensive international and regional comparisons of absolute gravimeters (AGs), nowadays usually organized under the auspices of metrological organizations [1] as key comparisons (KCs), a large amount of other bilateral and multilateral comparisons are continually taking place, both nationally and internationally. The purpose is for instance to control the performance of AGs between the KCs, to provide access to the KC reference values for AGs unable to participate in KCs, or to provide common reference for AGs participating in joint geodynamical or geodetic campaigns.

We report here of the Russian-Finnish comparison of AGs (RFCAG2013) in June-July 2013, where five AGs participated. Of particular interest are the GBL-M 002, the GABL-PM, and the GABL-M. These are field-type portable AGs made by Siberian Branch of Russian Academy of Sciences, Institute of Automation and Electrometry (IAE SB RAS, Novosibirsk). The RFCAG2013 is for them the first international comparison. The other two AGs are the FG5-110 of the Federal Scientific Research Center of Geodesy, Cartography and SDI (TsNIIGAiK, Moscow), and the FG5X-221 of the Finnish Geospatial Research Institute (FGI). The FG5X-221 provides the link to the Key Comparison Reference Value (KCRV) of the International Comparison of Absolute Gravimeters ICAG-2013 (CCM Key Comparison CCM.G-K2) in Luxembourg in November 2013.

AG comparisons are usually done at a single laboratory-type site. Our comparison however uses four different sites in Russia: Pulkovo, Svetloe, TsNIIGAiK, and Zvenigorod (Fig. 1). The differences between the site characteristics allow the assessment of AG performance over a wider range of external conditions. An additional useful outcome is the strengthening of time series of absolute gravity at these sites, all of which are of geodynamical in-

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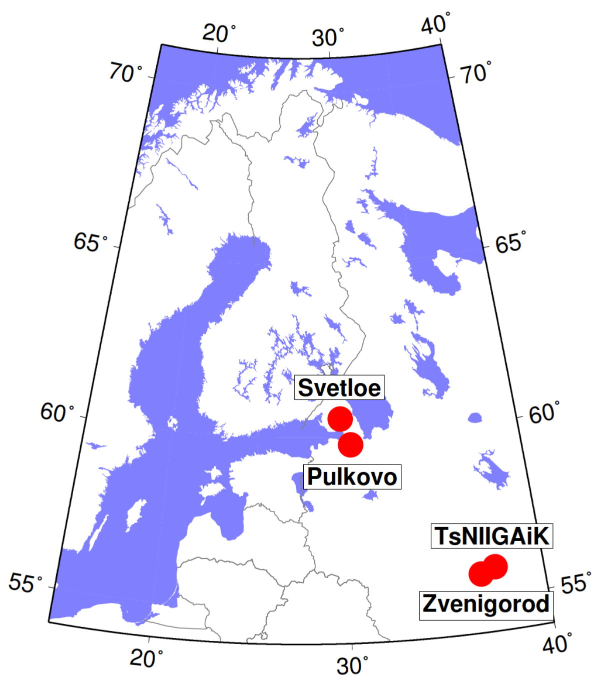

Figure 1: Location of the comparison sites.

terest. The time series aspect is not taken up in this paper. TsNIIGAiK and Zvenigorod have two piers each, such that the comparison was conducted using 6 different stations.

The RFCAG2013 is the fourth Russian-Finnish comparison in a sequence that started in 2004 at the Metsähovi Geodetic Observatory in Finland where also German teams participated [2]. It continued in 2005 at Zvenigorod, and in 2007 at Pulkovo and at Lovozero (Kola Peninsula; station not included in the present campaign).

2 Methods

2.1 Gravimeters, sites, gradient observations

The gravimeters are summarized in Table 1. The GABL-PM, the GABL-M and the GBL-M 002 are closely related as they represent an evolving series; the GBL-M 002 is the latest version. Some highlights are given in Table 2. For more details see [3].

The FG5-110 represents the original version of the FG5 gravimeter as described in [5], with a bulk interferometer and inclined legs of the dropping chamber tripod. The model FG5X is described in [6].

The locations of the sites are shown in Fig. 1. The occupation scheme is summarized in Table 3. The observations at a given station span 1–2 weeks. No correction for variation in gravity during this time was applied.

2.2 The vertical gradient of gravity

The dependence of gravity on the height above the station markers was determined using Scintrex CG-5 gravimeters, and the LaCoste&Romberg G-600 equipped with VRL feedback [6]. A second-degree polynomial in height was then fitted to the observations (Fig. 2). The polynomials are given in Table 4. At sites with piers the non-linearity is accentuated and then even the second-degree approximation could in principle be inadequate; its validity was checked using a model of pier attraction as described in [8].

2.3 Absolute gravity observations and processing

Observations with the FG5X-221 (at all stations) and with the FG5-110 (at most stations) were performed in two setups with opposing azimuths. This is a precaution against Coriolis effects due to possible horizontal velocity of the dropped object, and also against possible gross errors. No significant differences between the setups were seen. For the GABL-PM, the GABL-M and the GBL-M 002 measuring in two setups in opposing azimuths or in four setups 90 degrees apart is essential, in order to eliminate a known azimuth dependence due to magnetic influence in the drop mechanism. Analyzing the azimuth dependence is beyond the scope of this paper. We simply average over the two or four available azimuths.

For the FG5-110 and FG5X-221 one setup consisted typically of 15 to 40 sets of 50 drops and was taken overnight or during a working day. For the GABL-PM, the GABL-M and the GBL-M 002 one setup consisted of 5 to 9 sets of 80 or 100 drops, taken during 1–2 hours.

In the processing, gravity was referred to the effective height of the setup [4]. The observations were corrected for solid earth tides and ocean load tides, for the gravity variation due to atmosphere, and for polar motion as specified by the IAGBN Processing Standards [9] and the IERS Conventions [10]. There is a difference in the treatment of tides: for the FG5-110 and FG5X-221 the solid earth model is PREM and the ocean tide model FES2004 [11], both integrated in the "g" software provided by the manufacturer of the AG. For the GABL-PM, the GABL-M and the GBL-M 002, the tidal corrections were calculated using the IASPEI solid earth model [12], the FES2012 ocean tide model [13],

Table 1: The participating AGs. The gravimeters were operated by the authors of this paper. The effective height [4] depends, not only on gravimeter construction, but also on which interference fringes are used, and on the marker height above the mounting surface. It also varies from setup to setup. Here a nominal value above a flat mounting surface is given, in the configuration used in the comparison.

AG	Manufacturer	Owner	Operated by	Effective height
FG5X-221	Micro-g Lacoste	FGI	FGI	1.26 m
FG5-110	Micro-g Lacoste	TsNIIGAiK	TsNIIGAiK	1.22 m
GBL-M 002	IAE SB RAS	TsNIIGAiK	TsNIIGAiK	0.71 m
GABL-M	IAE SB RAS	NIIMorGeofisika	TsNIIGAiK	0.71 m
GABL-PM	IAE SB RAS	IAE SB RAS	IAE SB RAS	0.71 m

Table 2: Main features of the GABL-PM, GABL-M, GBL-M 002 gravimeters.
(1 μGal = 10^{-8} m s^{-2})

Straight line interferometer, fiber optics
Drop length 0.2 m
Effective height 0.7 m
Iodine-stabilized green laser
Automated camera-based setup of beam verticality
Weight 54 kg
Standard uncertainty 4.5 μGal + statistical scatter
Simple seismometer suspension (no SuperSpring) for reference prism gives large drop-to-drop scatter at noisy sites

Table 3: Station type and occupation schedule.

	Stations					
	Pulkovo	Svetloe	TsNIIGAiK 109a	TsNIIGAiK 110	Zvenigorod A	Zvenigorod B
Site type	Field lab	Field	Laboratory	Laboratory	Laboratory	Laboratory
Support	Pier	Floor	Pier	Pier	Floor	Floor
Gravimeter						
FG5X-221	June 12–14	June 19–21	June 24–26	June 26–27	June 29–30	June 28–29
FG5-110	June 14	June 16–17	June 28–July 2	July 3–5	July 5–6	July 6–7
GBL-M 002	June 8–9	June 12–13	July 2&11	June 21	June 30	June 29–30
GABL-M	June 9	June 11–12	July 3	July 1		
GABL-PM		June 14–15		June 24–25		

and the Atlantida 3.1 software [14]. The influence of the different treatments is included in the uncertainty estimation.

For the FG5-110 and FG5X-221 the self-attraction of the gravimeter was corrected for, using the results by [15] and [16], respectively. The diffraction correction is derived from [17], using nominal beam parameters for the FG5-110 and measured beam parameters for the FG5X-221. For the GABL-PM, the GABL-M and the GBL-M 002, neither the self-attraction nor the diffraction were corrected for.

The standard uncertainty for the GABL-PM, the GABL-M and the GBL-M 002 at the effective height is estimated to be 4.5 μGal excluding the contribution of the statistical scatter of the observations [3]. The corresponding figure for the FG5-110 and FG5X-221 is 2.3 μGal.

The corrected results for each setup were transferred to 1.000 m above the station marker, using the second-degree polynomial (Table 4). The two or four setups were averaged to form a station occupation value. Space does not allow us to present the details for all gravimeters. A typical calculation, for the GABL-M at the station TsNIGAiK 110 is shown in Table 5.

Table 4: Approximation of gravity as a function of height z above the station marker, using a second-degree polynomial $g(z) - g(0) = az+bz^2$ fitted by least squares to relative gravity observations. Here u_a and u_b are the standard uncertainties of the estimates a and b and $corr(a, b)$ is their correlation. The gravity difference between two heights z_1 and z_2 is then estimated by $\Delta g = g(z_1) - g(z_2) = a(z_1 - z_2) + b(z_1^2 - z_2^2)$ and its standard uncertainty as $m(\Delta g) = [u_a^2(z_1 - z_2)^2 + u_b^2(z_1^2 - z_2^2)^2 + 2u_a u_b\, corr(a, b)\, (z_1 - z_2)\, (z_1^2 - z_2^2)]^{1/2}$. The high negative correlation between a and b is caused by the choice of the station marker as the origin of the z-values: the marker is well outside the height range where the relative measurements are actually taken.

Coefficient	a	u_a	b	u_b	$corr(a,b)$
Unit	μGal/m	μGal/m	μGal/m^2	μGal/m^2	dimensionless
Pulkovo	−356.1	4.22	17.1	2.95	−0.969
Svetloe	−290.0	4.75	1.9	3.33	−0.973
TsNIIGAiK 109a	−344.5	4.50	12.5	2.90	−0.986
TsNIIGAiK 110	−349.6	4.94	15.6	3.51	−0.980
Zvenigorod A	−317.3	4.71	0.6	3.26	−0.978
Zvenigorod B	−321.9	8.00	4.0	5.57	−0.986

Table 5: Calculation of the station occupation value g at 1 m height for GABL-M at the station TsNIIGAiK 110 from the results at the effective height in four different azimuths. Only the last digits of the gravity values are shown. Some of the columns are self-explanatory. The transfer correction (column 7) from the effective height (column 2) to 1 m height and the standard uncertainty u_{Ti} (column 8) of the correction are derived from the second degree polynomial depicted in Fig. 2. Column 9 is then the sum of columns 3 and 7. The g is calculated as an average of the four g_i values in column 9. The standard uncertainty u of g is calculated as $u = [4.5 + (s_1^2 + s_2^2 + s_3^2 + s_4^2)/16 + (u_{T1}^2 + u_{T2}^2 + u_{T3}^2 + u_{T4}^2)/4]^{1/2}$, where 4.5 μGal is the standard uncertainty of a measurement at the effective height excluding statistical scatter, the s_i are the 4 standard deviation values in column 6, and the u_{Ti} are the four transfer uncertainties in column 8.

1	2	3	4	5	6	7	8	9
Azimuth	Eff. height	Result	S.D. of set SD$_i$sets	N mean s_i =SD$_i/\sqrt{N}$	S.D. of to 1 m	Transfer u_{Ti}	Std. uncert. g_i	Result at 1 m
	m	μGal	μGal		μGal	μGal	μGal	μGal
N	0.716	677.7	11.1	5	5.0	−91.7	0.4	586.0
S	0.715	659.6	15.5	5	6.9	−92.0	0.4	567.6
E	0.711	659.8	12.8	5	5.7	−93.3	0.4	566.5
W	0.716	664.2	14.8	5	6.6	−91.7	0.4	572.3
g = result of station occupation at 1 m (average of 4 azimuths)								573.1
u = standard uncertainty								5.6

3 Results

The FG5X-221 is the only AG in our comparison that has participated in a Key Comparison (the CCM.G-K2), and thus the link to KCs will take place exclusively through the FG5X-221. It is therefore convenient to present the results of the AGs with the result of the FG5X-221 subtracted. The results at the 6 stations at the 1 m comparison height are given in Table 6 and in Fig. 3. They show that the offsets relative to the FG5X-221 are quite consistent for each gravimeter from station to station.

For gravimeters other than the FG5X-221, Table 6 has two uncertainty columns. The column labelled "U" is the expanded uncertainty of the AG at 1 m height. The column labelled "U_r" is the expanded uncertainty of the difference between the AG and the FG5X-221. It is calculated from $U_r = [U^2 + U_0^2]^{1/2}$ where U_0 is the expanded uncertainty of the result of the FG5X-221. Here we neglect the minor correlation between the FG5X-221 and the other gravimeters, due to the transfer to the 1 m level using the same model for $g = g(z)$.

One could now refer the AGs to the KCRV of the CCM.G-K2 already at each of the 6 stations separately, using the offset of the FG5X-221 at the CCM.G-K2. The associated uncertainties relative to the KRCV would however be appreciably correlated as they all share the uncertainty of the FG5X-221 offset at the CCM.G-K2. This would lead to a somewhat opaque treatment in combining the station-wise offsets relative to the KCRV rigorously to a mean offset. Therefore we prefer to first combine the offsets relative to the FG5X-221. The calculation is in Table 6. The mean offset is calculated using the $(1/U_r)^2$ as weights. The resulting val-

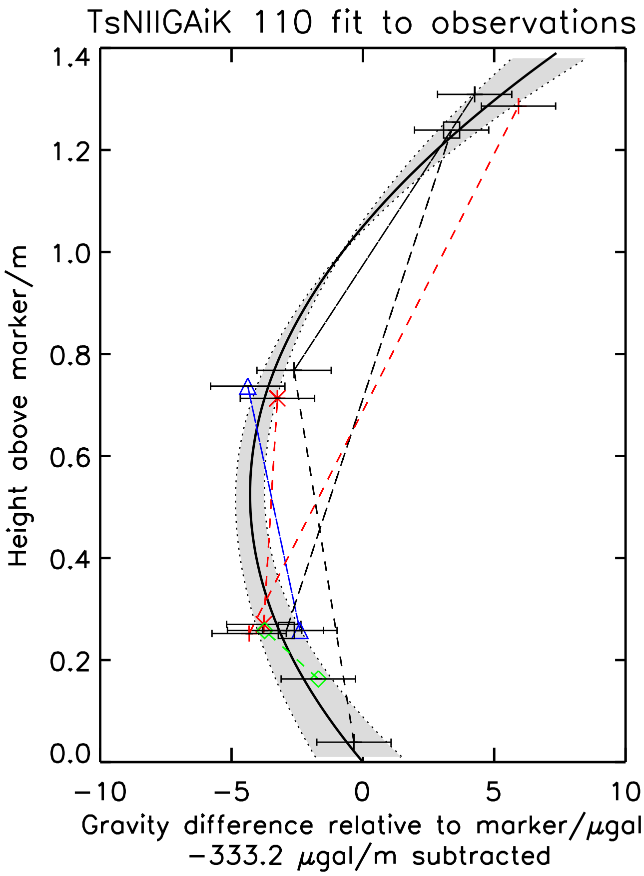

Figure 2: Relative measurements of gravity differences (the chords) and the fitted second-degree polynomial (the solid curve) above the station marker at the station TsNIIGAiK 110. Height above the marker is on the vertical axis and gravity is on the horizontal axis. To make the deviation from linearity better visible a mean vertical trend of −333.2 µGal/m has been subtracted from observations and from the fitted polynomial before plotting. The error bars show the estimated standard uncertainty of $\sqrt{2}$ µGal for gravity values (i.e., 2 µGal for gravity differences). This uncertainty is used in the polynomial fit, instead of the standard deviation derived from the elimination of drift in the relative observation series. The latter figure would typically be much smaller and is considered unrealistic. Shading shows the standard uncertainty of the gravity difference determined from the fitted polynomial relative to the height 1.000 m, where the absolute-gravity values are compared. The numerical values are in Table 4.

ues and their uncertainties are in the second-to-last row of Table 6. The last row contains the RMS of the uncertainties U_r, needed in the sequel in the assessment of the Degree of Equivalence (DoE)[1] of the gravimeters.

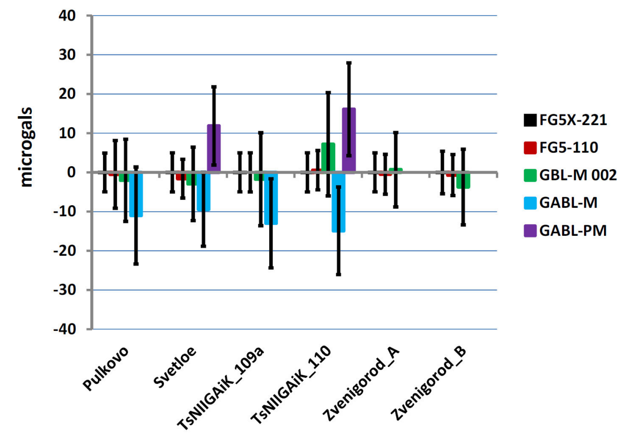

Figure 3: The station-by-station results of the RFCAG2013. The gravity values are shown with the result of the FG5X-221 subtracted. They come from the columns "g" in Table 6 except for the FG5X-221 which is put to zero. The error bars show the expanded uncertainty (95% confidence). They come from the columns "U" in Table 6. Note that subtracting the results of the FG5X-221 is here only a presentation device: the FG5X-221 uncertainties are plotted around zero and the uncertainties for the other AGs are those of their own measurements and not those of the difference AG minus FGX-221. At each station the gravimeters are in the same order as in the legend entry. Thus they can be identified even without the colors.

We now are ready to assess the DoE of the AGs in the RFAG2013 relative to the KCRV of CCM.G-K2. In Table 7 we add the offset of the FG5X-221 relative to KCRV of the CCM.G-K2 (+1.5 µGal) and its expanded uncertainty (3.3 µGal), both from Francis et al. [1], to the mean offset of the AG relative to the FG5X-221. The results are in its bottom row.

As discussed in [1], the uncertainty of the offset (in column "U_1") is not appropriate for assessing DoE. The uncertainty of the offset describes how well the offset was determined in the comparison. It decreases with the number of station occupations N approximately as $N^{-1/2}$ and using it for assessing equivalence would imply that with increasing number of stations we require the mean offset of the AG

1 In the use of the term "Degree of Equivalence" (DoE), we adhere to the definition in the document CIPM MRA-D-05 [18]. We quote from page 4: "The degree of equivalence relative to the key comparison reference value of a measurement standard or of a measurement result is the degree to which the measured value is consistent with the key comparison reference value. This is expressed quantitatively by two terms: the deviation from the key comparison reference value and the expanded uncertainty of this deviation computed at a 95 % level of confidence (in practice, this is often approximated by using a coverage factor k equal to 2)". In contrast to the CIPM MRA-D-05, some recent literature (e.g. [1]) uses "DoE" interchangeably with the "deviation" of the quote above; or offset in terminology of this paper. This recent use appears to us ill-advised: after all, such a deviation is meaningless without an associated uncertainty.

Table 6: The station-by-station results of the RFCAG2013. The columns labelled "g" give the results of the AGs at the stations at 1 m height. The last digits of the results of the FG5X-221 are shown; they are subtracted from the other gravimeters. The columns labelled "U" (U_0 for the FG5X-221) give the uncertainties of the results. The columns labelled "U_r" give the uncertainties of the difference between the AG and the FG5X-221, calculated from $U_r = [U^2 + U_0^2]^{1/2}$. The first row below the station rows gives in the "g" column the weighted mean of the 2–6 differences between the AG and the FG5X-221, with the $(1/U_r)^2$ of the station rows as weights. The "U_r" column in this row gives the uncertainty of the difference. The lowest row gives the RMS of the 2–6 values U_r. All units are microgals and all uncertainties are expanded uncertainties (95% confidence). More comments in text.

Gravimeter	FG5X-221		FG5-110			GBL-M 002			GABL-M			GABL-PM		
	g	U_0	g	U	U_r	g	U	U_r	g	U	U_r	g	U	U_r
Pulkovo	228.3	4.9	−0.5	8.6	9.9	−2.0	10.5	11.6	−11.0	12.4	13.3			
Svetloe	712.3	5.0	−1.6	4.9	7.0	−2.9	9.4	10.6	−9.4	9.4	10.7	11.8	10.0	11.1
TsNIIGAiK 109a	619.2	5.0	0.0	5.0	7.1	−1.8	11.9	12.9	−13.0	11.4	12.4			
TsNIIGAiK 110	588.0	5.0	0.6	5.0	7.1	7.2	13.2	14.1	−14.9	11.2	12.3	16.1	11.9	12.9
Zvenigorod A	824.0	5.0	−0.5	5.1	7.1	0.7	9.5	10.7						
Zvenigorod B	824.2	5.4	−0.7	5.2	7.5	−3.7	9.7	11.1						
Mean at stations			−0.4		3.0	−0.9		4.8	−11.9		6.0	13.7		8.4
RMS of U_r					7.7			11.9			12.2			12.0

to converge towards zero for the gravimeter to be in equivalence.

However, the DoE is supposed to address the issue whether the offset is compatible with the declared uncertainty of measurements with the AG. Thus we follow [1] and use the RMS expanded uncertainty of the 2–6 station occupations relative to the FG5X-221, adding to it the expanded uncertainty of the offset of the FG5X-221 in CCM.G-K2. The resulting expanded uncertainties are in the bottom row of Table 7 in the column labelled "U_2". They provide the required assessment of the Degree of Equivalence together with the offsets "g" in the same row. These offsets and expanded uncertainties are also plotted in Fig. 4. We find that for all AGs except the GABL-PM KRCV the offset from the KRCV of the CCM.G-K2 is less than the expanded uncertainty, i.e., they are in equivalence with the KRCV.

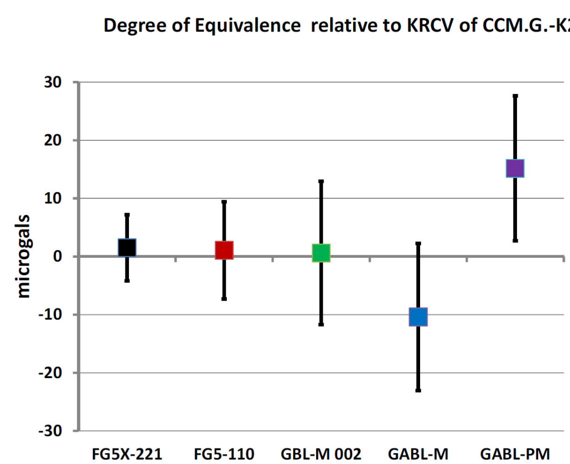

Figure 4: Final RFCAG2013 results: the offsets of the 5 AGs relative to the KCRV of CCM.G-K2, with expanded uncertainties (95% confidence). The offsets for the FG5-110, the GBL-M 002, the GABL-M, and GABL-PM come from the column "g" of the last row of Table 7, and their uncertainties from column "U_2" of the same row. The values for the FG5X-221 are from the CCM.G-K2. For all AGs except the GABL-M the offset is less than the expanded uncertainty, i.e. they are in equivalence with the KRCV of the CCM.G-K2.

4 Discussion

We have presented results of one of the first comparisons of AGs that is explicitly tied to the KRCV of a Key Comparison. This RFCAG2013 is also the first international comparison for the Russian series of portable field-type AGs made by the IAE SB RAS. Despite quite variable station conditions, the three AGs by IAE SB RAS show very consistent offsets at the 2–6 comparison stations at which they observed. One of them is not in equivalence.

The results provide an occasion to reflect on current and future practices in absolute gravimetry (Marti et al. [19]). While the RFCAG2013 is not a calibration of AGs in the metrological practice as foreseen by Marti et al. [19], its structure and the treatment of the data are indistinguishable from one. It is likely that in the future, offset corrections will be assigned on the basis of such calibrations to the participating gravimeters. This is in fact already happening in geophysical campaigns and in the measurement of national networks with portable AGs, where their results typically are corrected using offset estimates derived from comparisons with laboratory-type AGs. The first au-

Table 7: Final results of the RFCAG2013. The top row is from Table 6 and contains in column "g" the mean offset of the AG relative to the FG5X-221 at the 2–6 stations, in column "U_1" the uncertainty of the offset, and in column "U_2" the RMS of the 2–6 uncertainties. In the second row we then add in the column "g" the offset of the FG5X-221 at CCM.G-K2 and in columns "U_1"and "U_2" its uncertainty, from [1]. In the bottom row we then obtain the offset of the AG relative to the KCRV of the CCM.G-K2 (in column "g"), its uncertainty (in column "U_1"), and the uncertainty (in column "U_2") for assessing the Degree of Equivalence. All units are microgals and all uncertainties are expanded uncertainties (95% confidence). More comments in text.

Gravimeter	FG5-110			GBL-M 002			GABL-M			GABL-PM		
	g	U_1	U_2	g	U_1	U_2	g	U_1	U_2	g	U_1	U_2
Mean offset to FG5X-221	−0.4	3.0	7.7	−0.9	4.8	11.9	−11.9	6.0	12.2	13.7	8.4	12.0
Add offset of FGX-221 at CCM.G-K2 and its uncertainty	1.5	3.3	3.3	1.5	3.3	3.3	1.5	3.3	3.3	1.5	3.3	3.3
Offset of gravimeter relative to the KCRV of CCM.G-K2, its uncertainty, and the uncertainty for assessing equivalence	1.1	4.5	8.4	0.6	5.8	12.3	−10.4	6.9	12.6	15.2	9.0	12.5

thor has recently argued that this amounts to using the calibrated AGs as relative instruments (J. Mäkinen, The return of relative gravimetry, 26th IUGG General Assembly, Symposium G02 Static Gravity Field Models and Observations. Prague, June 22 to July 2, 2015). To some extent this is a semantical question, but it is clear that when such procedures are applied, for all practical purposes the size of the offset of the calibrated AG is unimportant, and only the stability of the offset matters.

On another note, look at the uncertainty of the offset of the FG5-110 relative to the KRCV of the CCM.G-K2 in the pertinent column "U_1" of Table 7. The FG5X-221 went to the CCM.G-K2, observed three stations only, and got an expanded uncertainty of 3.3 μGal relative to the KCRV. Now the FG5-110 and the FG5X-221 did 6 stations together in the RFCAG2013 and the FG5-110 still could not get smaller than the 4.5 μGal expanded uncertainty relative to the KCRV. Why is that? The explanation obviously is the unfavourable propagation of uncertainties in a tree-like calibration structure. For the FG5-110 the KCRV is only accessible through the FG5X-221; at each of the 6 stations the uncertainty for the FG5-110 is combined with the uncertainty for the FG5X-221. Thus from the viewpoint of propagation of uncertainties, large-scale simultaneous comparisons of AGs have a distinct advantage over a calibration tree.

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